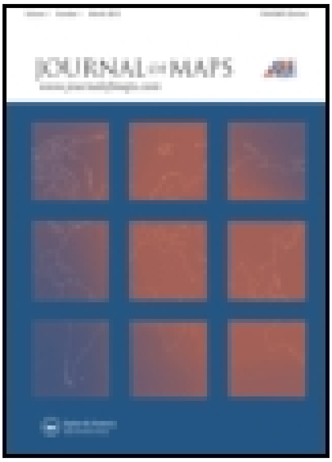

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SCIENCE

Geology and Jurassic paleogeography of the Mt. Primo-Mt. Castel Santa Maria ridge and neighbouring areas (Northern Apennines, Italy)

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This paper presents the results of a geological mapping project across the Mt. Primo ridge and neighbouring areas (Umbria-Marche Domain – Northern Apennines), where a thick Meso-Cenozoic carbonate succession is exposed. A geological map on the 1:15,000 scale, illustrates the main stratigraphic, paleogeographic and structural features of the area. The geometries of Jurassic stratigraphic units, were mainly controlled by the complex submarine topography resulting from an Early Jurassic extensional phase. The three-dimensional distribution of Jurassic rocks in turn conditioned the structural evolution of this part of the Apennines during the chain building phase.

Keywords: Jurassic stratigraphy; pelagic carbonate platforms; Northern Apennines; Umbria-Marche basin; Calcare Massiccio; submarine paleoescarpments

1. Introduction

A Main Map is presented here, displaying the geology of a portion of the so-called 'Umbria-Marche ridge' (Northern Apennines), which is the westernmost of the two main ridges that form the Umbria-Marche Apennines (Figure 1) (Centamore & Micarelli, 1991). The map covers an area about 50 km^2 wide, located in the westernmost sector of the Marche region (Province of Macerata) and falls within the drainage basin of the Potenza river; the main villages in the area are Pioraco and Sefro (Figure 1). The E/W trending Potenza river valley, and the SSW/NNE trending valley of the Scarsito river (which joins with the Potenza river at Pioraco) separate three main ridges (Mt. Primo, Mt. Gualdo and Mt. Castel Santa Maria). The higher elevations exceed 1000 m (Mt. Primo, 1299 m; Mt. Castel Santa Maria, 1238 m), while the valley bottoms lie at an average elevation of 400–500 m asl. In this portion of the Apennines, a regular pattern of NNW-SSE aligned anticlines and subparallel synclines was produced by the mountain chain building, and controls the distribution of ridges and valleys in the present-day topography (Cresta, Monechi, & Parisi, 1989). Nevertheless, prior to being involved in the mountain chain building, the area was affected by a major extensional phase in the Early Jurassic, resulting in a submarine paleotopography which would produce a strong lateral variability of facies and thickness in the carbonate succession during the remainder of the Jurassic. The study area bears compelling field evidence for this rift phase.

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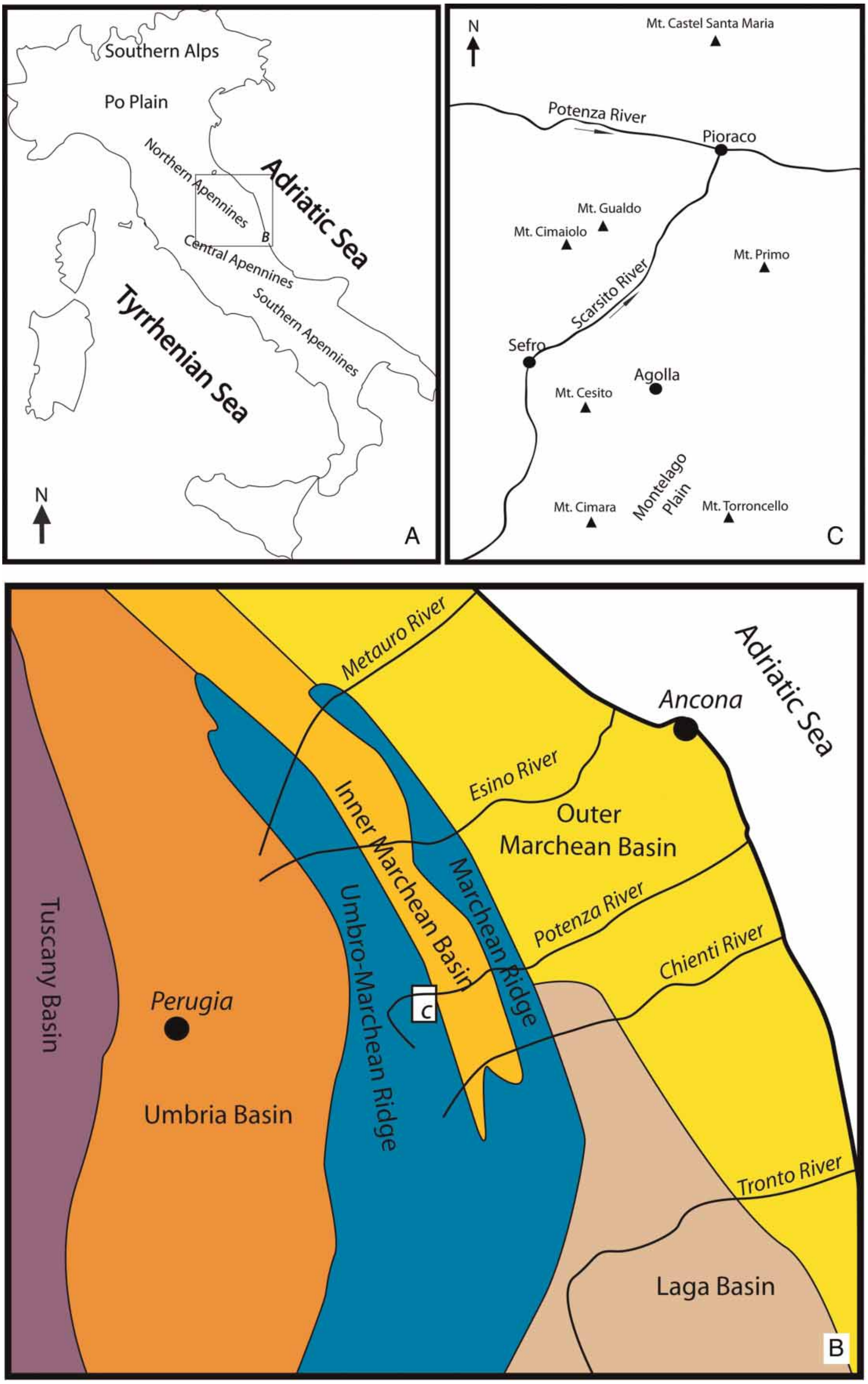

Figure 1. Regional overview and location of the study area.

2. Methods

The map is the result of a detailed geological survey originally performed at 1:10,000 scale, using an enlarged 1:25,000 IGM topographic map. Lithostratigraphy was supported by paleontological analysis (in thin section), and integrated with methods of facies analysis which are specific of extended and drowned carbonate platforms in the Tethyan Jurassic (Santantonio, 1993, 1994; Santantonio, Galluzzo, & Gill, 1996). Pelagic facies associations at rifted carbonate margins typically have a lateral distribution and vertical evolution that are tightly linked with the local morpho-tectonic architecture, which commonly exists in the form of a rugged submarine topography. Recognition in the field of the angular unconformities separating the extended pre-rift substrate (Calcare Massiccio Fm), exposed at footwall margins, from the hangingwall basin formations, is the key step for interpreting this architecture.

3. Stratigraphy and geological setting

The stratigraphic succession of the study area (Figure 2) is regionally known as the Umbria-Marche succession (Centamore, Chiocchini, Deiana, Micarelli, & Pieruccini, 1971). The Jurassic stratigraphy

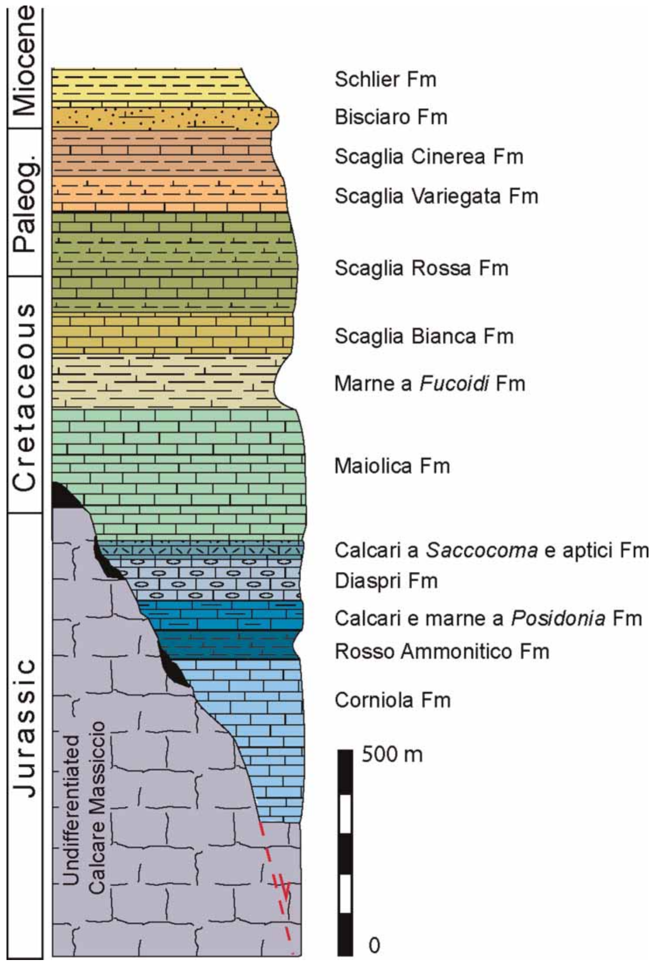

Figure 2. General stratigraphy of the study area. In black are indicated the condensed deposits belonging to the Bugarone Group (thickness exaggerated); the thickness of the Scaglia Variegata to Schlier formations is inferred.

of the Umbria-Marche region was controlled, as mentioned above, by the complex submarine topography produced by an early Jurassic extensional phase (Centamore et al., 1971; Colacicchi, Passeri, & Pialli, 1970; Farinacci, Mariotti, Nicosia, Pallini, & Schiavinotto, 1981).

Facies associations in these depositional systems have been described by Santantonio (1993), who identified different types of pelagic carbonate platforms (PCPs) corresponding to intrabasinal highs (Santantonio, 1994). The margins of these PCPs were submarine escarpments produced by the Early Jurassic extensional faults (Alvarez, 1990; Bice & Stewart, 1985; Carminati & Santantonio, 2005; Santantonio & Carminati, 2011). These escarpments could host local patches of condensed sediment (epi-escarpment deposits), before being progressively onlapped by the basin-fill succession (Figure 3). A remarkable feature of paleoescarpments is that they can be pervasively silicified, where unconformably overlain by pelagic units with silica-rich diagenetic fluids (Santantonio et al., 1996) (Figure 4). The recognition of chert nodules and crusts in the Calcare Massiccio (see below) provides sound evidence for identifying Jurassic basin margins in the field.

The Jurassic starts with the Calcare Massiccio Fm, a regional carbonate megabank, which was dismembered by late Hettangian-Sinemurian extension into structural highs and lows, having a different structural and stratigraphic evolution (Donatelli & Tramontana, 2014; Fabbi & Santantonio, 2012; Marino & Santantonio, 2010; Santantonio, 1994); for this reason the Calcare Massiccio Fm has been differentiated into three informal units (Figure 5) following Cita et al. (2007).

The Calcare Massiccio Fm *s.s.* (‘Calcare Massiccio A’ in Centamore et al., 1971 – Hettangian-Sinemurian *p.p.*) represents the pre-rifting shallow water carbonate platform, characterized by cyclic sedimentation. It is made of white, thick bedded to massive (Figure 6a) grainstone and packstone, containing molluscs (gastropods and bivalves – Figure 6b), ooids, oncoids, peloids, ostracods, *Lithocodium/Bacinella* assemblages, benthic forams (Valvulinidae, Lagenidae, Nubecularidae, *Trocholina* sp.) and algae (Dasycladaceae, in particular *Palaeodasycladus* sp., Solenoporaceae, *Cayeuxia* sp.). Red levels rich in vadose pisoids and Fe-oxides indicate phases of subaerial exposure. The maximum exposed thickness is >650 m, as seen at Mt. Primo.

The drowning of carbonate platform structural lows (Hettangian/Sinemurian boundary, Passeri & Venturi, 2005), was clearly linked with tectonic subsidence along synsedimentary

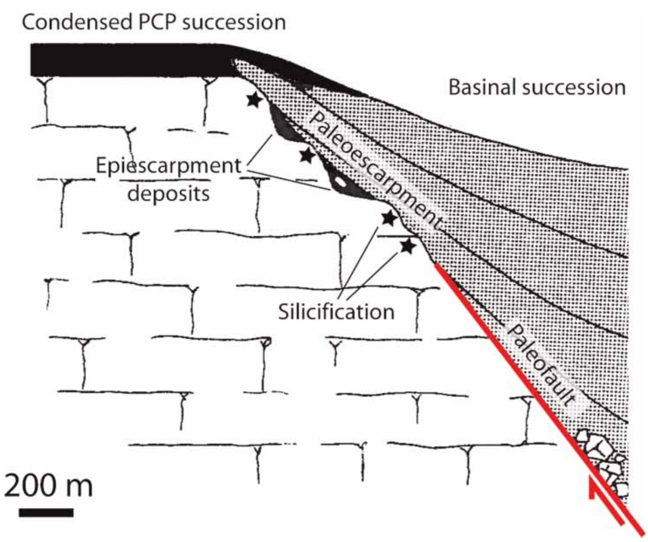

Figure 3. Main paleotectonic and stratigraphic features of the PCP-basin systems. Modified after Santantonio, (1994).

Figure 4. Typical appearance of Calcare Massiccio silicified paleosurfaces.

faults. By contrast, the inception of condensed pelagic sedimentation on PCPs was the result of a regionally synchronous drowning of the small surviving fault-bounded carbonate banks in the early Pliensbachian, possibly due to climate-related eutrophication of the environment, evidenced by a positive δ^{13}C shift (Morettini et al., 2002). The Calcare Massiccio B Mbr (Sinemurian *p.p.* – early Pliensbachian *p.p.*) represents the drowning succession of carbonate platform footwall blocks, and is a fine, generally hazel-colour, grainstone/packstone, organized in decimetric to metric beds. Skeletal components are mainly bioclasts (algae, bivalves, brachiopods), microbial oncoids and crusts, peloids, sponge spicules, radiolarians, benthic forams (*Agerina martana, Involutina* sp.*,* Lagenidae), *Tubyphites* sp. and small gastropods. The mud fraction increases upwards, parallel to the relative abundance of radiolarians and sponge spicules, testifying the ongoing drowning of the benthic carbonate factory and the onset of a pelagic environment. The maximum thickness is ca. 40 m at Mt. Cimara. The Calcare Massiccio C lithofacies (drowning succession of hangingwall blocks) does not outcrop in the study area, nevertheless a transition from peritidal to pelagic sedimentation that took place at the hangingwall of an embryonic Jurassic fault is marked by low-angle clinoform sets at Pioraco (Fabbi & Santantonio, 2012).

Above the Calcare Massiccio Fm, Sinemurian to Tithonian deep water pelagic and turbiditic deposits regionally represent a thick (up to more than 1.5 km, Galluzzo & Santantonio, 2002) succession deposited in hanging-wall basins. Almost the same time span, starting in the early

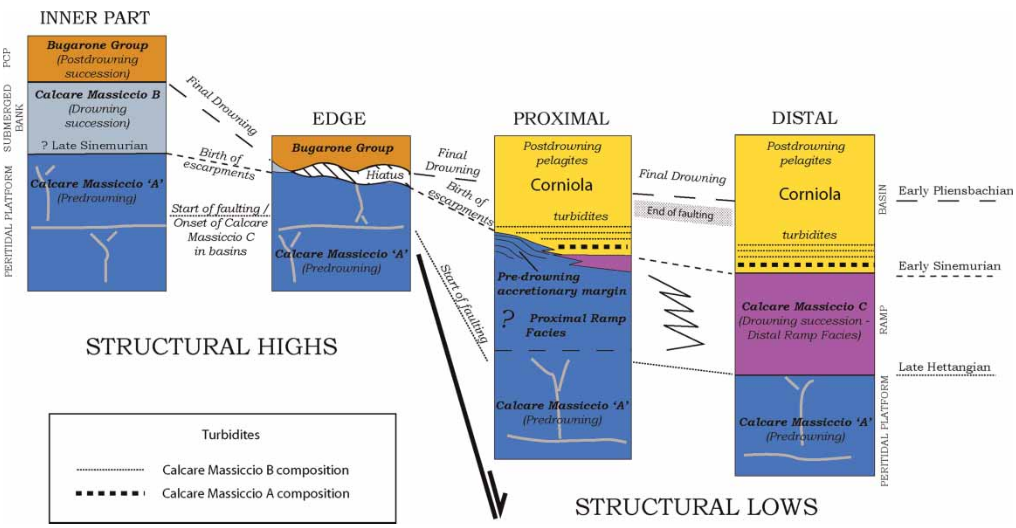

Figure 5. Litho-chronostratigraphic and event correlation, and general facies along a typical PCP-basin transect (early post-drowning scenario). Modified after Fabbi & Santantonio, 2012.

Pliensbachian, is covered by a condensed pelagic succession on intrabasinal highs in no more than a few tens of metres (Figure 3). Basin margin successions locally bear isolated megaclasts produced by escarpment retreat, reaching hundreds metres (up to 2000 m) in size (Di Francesco, Fabbi, Santantonio, Bigi, & Poblet, 2010; Fabbi & Santantonio, 2010; Galluzzo & Santantonio, 2002).

The oldest pelagic unit is the Corniola Fm (Sinemurian *p.p.*-Pliensbachian), a grey-hazel cherty mudstone and wackestone containing abundant radiolarians and sponge spicules, and less abundant brachiopods, ostracoda and benthic forams (*Agerina martana*), along with rare ammonoids. The lower portion bears great volumes of benthic material and lithoclasts, sourced from the neighbouring, still productive carbonate platform structural highs, and organized in thick graded and laminated beds (Figure 6c). Following the end of benthic carbonate production in the early Pliensbachian, basinal successions became almost free of any coeval resedimented material of shallow water origin. The upper portion of the unit is therefore a well-bedded pelagic mudstone with white chert nodules. This unit reaches a maximum thickness of ca. 400 metres in the Potenza valley, and the resedimented material it contains was likely sourced by the Mt. Primo high. Above the Corniola Fm, the Rosso Ammonitico Fm (Toarcian *p.p.*) is a red nodular marly limestone/marl alternation, bioturbated, containing abundant ammonoids (Canavari, 1879, 1892; Fucini, 1911), rare brachiopods, ostracods and thin-shelled bivalves; chert is absent. The onset of sedimentation of such a clay-rich unit within a carbonate-dominated pelagic basin can be related to the global carbonate production crisis that occurred in the early Toarcian (Jenkyns, 1988). The Calcari e marne a *Posidonia* Fm (late Toarcian – early Bathonian *p.p.*) is made of reddish/grey marly limestones and marls (Figure 6d) with chert, the latter abruptly increasing upsection. Faunal assemblages are dominated by pelagic thin-shelled bivalves (*Bositra buchii* and *Lentilla humilis* = *Posidonia auctt.*), along with radiolarians and rare ammonoids. The latter unit passes upwards to the Diaspri Fm (early Bathonian *p.p.* – early Kimmeridgian *p.p.*), an alternation of very thin cherty mudstone, and 5 to 20 cm-thick intervals of reddish/green chert beds (Figure 6e). The fauna consists almost exclusively of radiolarians. Graded and laminated coarse-grained levels (up to 60 cm thick) also occur. Coeval cherts are known in the entire Tethyan realm, as a result of ocean water eutrophication in the Middle-to-Late Jurassic (Bartolini

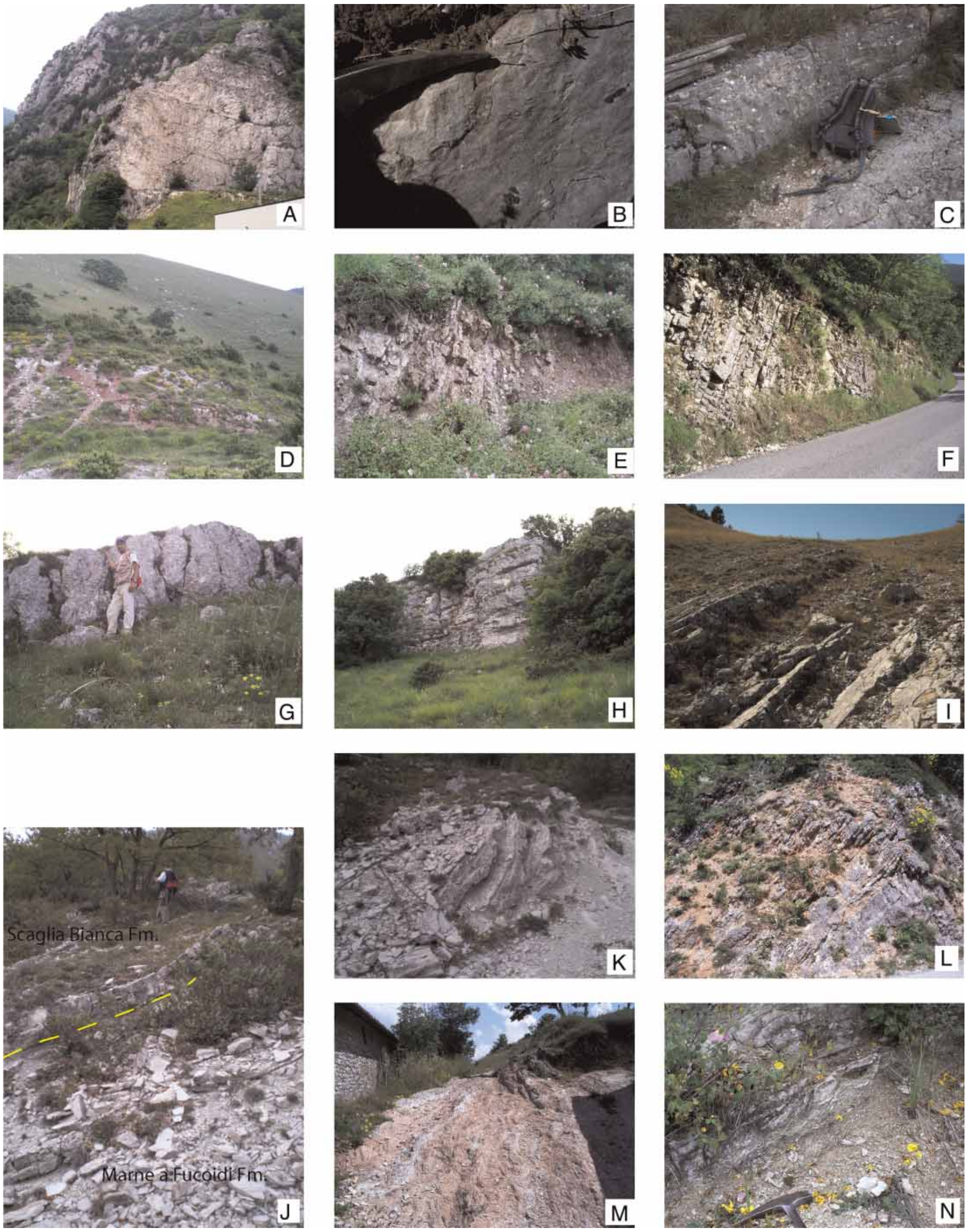

Figure 6. Field view of the main stratigraphic units described in the text: (A) and (B) Calcare Massiccio A; (C) Corniola Fm; (D) Rosso Ammonitico Fm; (E) Calcari diasprigni Fm; (F) Maiolica Fm; (G) Lensoid breccia bed within the Maiolica Fm (Mt. Primo); (H) and (I) Coarse thick beds in the Maiolica Fm (Mt. Primo); (J) Transition between the Marne a Fucoidi Fm and the Scaglia Bianca Fm; (K) Marne a Fucoidi Fm; (L) Scaglia Rossa Fm; (M) Scaglia Variegata Fm; (N) Scaglia Cinerea Fm.

& Cecca, 1999). The Diaspri Fm is followed by the Calcari a *Saccocoma* e Aptici Fm (early Kimmeridgian *p.p.* – late Tithonian *p.p.*), a cherty limestone bearing abundant remains of the crinoid *Saccocoma* sp., along with Aptychi, assorted bioclasts and rare ammonoids (*Aspidoceras* sp.). The latter four formations generally outcrop continuously, with an estimated total thickness of up to 280 m. While this part of the Jurassic succession has been also subdivided based on chert content, producing one stratigraphic unit (Calcari diasprigni Fm) to include the upper part of the Calcari e marne a *Posidonia*, the Diaspri Fm and the Calcari a *Saccocoma* e Aptici Fm (Cita et al., 2007; Servizio Geologico d'Italia, 2009; Servizio Geologico d'Italia, in press a, b), for the purposes of the present project, the subdivision proposed by Galluzzo and Santantonio (2002), where 'the lithogenetic role played by specific biogenous components' (*Posidonia*/radiolarians/ *Saccocoma*) is emphasized, has been utilized. This approach proved entirely feasible in the field, allowing for greater detail on map.

The above described basinal succession is replaced on intrabasinal highs by a condensed pelagic succession, made up of four informal units, which were originally described in the literature as members of the 'Bugarone Fm' (Centamore et al., 1971). The Bugarone rose recently to Group status, following a lithostratigraphic revision supervised by the Geological Survey of Italy within the CARG (Geological Map of Italy) project. Condensed units can either be found representing the PCP-top succession or in the form of scattered deposits in perched-pond settings along paleoescarpments. The distinctive field features of condensed units are the abundant macrofauna (ammonoids, belemnites, brachiopods, bivalves, crinoids), and the total lack of chert and resedimented deposits. An ideal condensed succession starts with the 'Calcari nodulari dell'Infenaccio' (early Pliensbachian *p.p.* – early Toarcian. *p.p.*), a nodular hazel-coloured micritic limestone organized in dm-thick beds, with abundant macrofauna (ammonoids, bivalves, brachiopods) and microfauna (sponge spicules, crinoids, radiolarians, benthic forams); it is conformably overlain by the 'Calcari nodulari e marne Verdi de I Ranchi' (Toarcian *p.p.*), a nodular yellow micritic marly limestone, incipiently dolomitized, in dm-thick beds; the latter is in turn overlain by the 'Calcari nodulari a filaments di Fosso del Presale' (late Toarcian *p.p.* – early Bajocian), a brown micritic limestone with thin-shelled bivalves, radiolarians, sponge spicules and small ammonoids; the condensed succession ends with the 'Calcari nodulari ad ammoniti e aptici di Cava Bugarone' (early Kimmeridgian *p.p.*– ?late Berriasian *p.p.*) a yellow lime wackestone, partly dolomitized, organized in dm-thick beds, richly ammonitiferous, with common aptychi, belemnites and fragments of bivalves; the microfauna is dominated by *Saccocoma* sp., along with radiolarians and calpionellids. It is worth noting that a condensed facies of the Maiolica Fm is described in the literature (Micarelli, Potetti, & Chiocchini, 1977; Parisi, 1989), locally representing the uppermost part (upper Tithonian – Berriasian) of the condensed PCP succession, conformably following the 'Calcari nodulari ad ammoniti e aptici di Cava Bugarone'. Note however that this facies has many characteristics in common with the Bugarone Group (e.g.: absence of chert, condensation with cephalopods locally in rock-forming quantities, nodular structure). Obvious similarities with the Maiolica only include colour (this unit is a whiter shade of pale than the typical Bugarone) and the occurrence of calpionellids, the latter being only identifiable in thin section. For the above reasons, an approach more firmly rooted on field observations and lithostratigraphy (e.g.: 'drastic fall in macrofossil content and textures change from wackestone to mudstone' – Galluzzo & Santantonio, 2002) was preferred here, leading to the inclusion of the lower Cretaceous ammonite-rich condensed facies in the Bugarone Group ('Calcari nodulari ad ammoniti e aptici di Cava Bugarone'). The stratigraphic gap between 'Calcari nodulari a filaments di Fosso del Presale'and 'Calcari nodulari ad ammoniti e aptici di Cava Bugarone' was first evidenced through ammonite biostratigraphy by Cecca, Cresta, Pallini, & Santantonio (1985). Only very limited portions of the condensed succession crop out in the study area (at Mt. Cimara and south of Sefro); by contrast, condensed units commonly crop out as scattered patches of epiescarpment or epibreccia deposits, resting on a silicified Calcare Massiccio surface. The total thickness of condensed successions exposed in the area is less than 15 m. The 'Calcari nodulari a filaments di fosso del Presale' crops out south of Mt. Gualdo, but the outcrop was below mapping resolution.

The Jurassic submarine relief was finally blanketed in the Early Cretaceous by the Maiolica Fm (late Tithonian *p.p.* – early Aptian *p.p.*). This white, well-bedded (Figure 6f) cherty mudstone is a widespread pelagic facies in the whole Tethyan realm, a result of the calcareous nannoplankton bloom which occurred in the latest Jurassic (Erba, 2006). The microfauna is also composed by calpionellids and radiolarians. At Mt. Primo, this unit bears polygenic clastic lensoid beds resulting from submarine sliding (Figure 6g), and also graded and laminated beds interpreted as turbidites (Figure 6h and i), containing benthic material sourced from productive carbonate platforms located outside of the study area, which must have escaped the widespread phase of Early Jurassic drowning. The Maiolica crops out extensively, amounting to a maximum thickness of more than 300 m at Mt. Primo, where the top is not exposed. Typically in the region the Maiolica Fm can both onlap and silicify the Calcare Massiccio paleoescarpments, or conformably cover the tops of PCPs.

Selected microfacies of the described units are shown in Figure 7.

The Maiolica is followed by the Marne a Fucoidi Fm (early Aptian *p.p.* – Albian), a green/grey succession of marl and marly limestone (Figure 6k), with only rare chert nodules. About 1 meter above the base of the unit a bitouminous interval ('Selli level' – Coccioni, Nesci, Tramontana, Wezel, & Moretti, 1987) is present. The lower portion of the formation is rich in laminated calcarenites. Paleontological content is represented by abundant planktonic forams (*Planomalina* spp., *Ticinella* spp., *Hedbergella* spp.) and by ichnofossils (*Chondrites* sp. = *'Fucoidi' auctt.).* The maximum thickness exceeds 100 m. A gradual increase of calcareous beds (Figure 6j), along with the appearance of common black chert bands, mark the passage to the Scaglia Bianca Fm (Cenomanian – early Turonian *p.p.*), made by mainly mudstone 10 to 30 cm-thick beds, with abundant planktonic forams (*Rotalipora* spp.*, Planomalina* spp., *Shackoina* spp., *Biticinella* spp.). Near the top of the unit, the 'Bonarelli level' is a ca. 1 m-thick bituminous level which represents a regional stratigraphic marker, related to the Oceanic Anoxic Event 2 (latest Cenomanian, Jenkyns, 1985). A few metres above the 'Bonarelli level', the limestone becomes red or pink (Figure 6l), with red/brown chert bands, marking the passage to the Scaglia Rossa Fm (early Turonian *p.p.* – middle Eocene *p.p.*). This is characterized by abundant foraminifer assemblages (belonging to the genera *Globotruncana, Marginotruncana, Dicarinella, Contusotruncana, Abatomphalus, Gansserina, Globorotalia, Morozovella, Turborotalia* among others*)*. The Scaglia Bianca-Scaglia Rossa formations reach a cumulative thickness of not less than 280 m.

Units younger than the Scaglia Rossa Fm only crop out at the front of the Mt. Primo structure, as horses in the intermediate tectonic unit of the local thrust system (see below). The Scaglia Variegata Fm (middle Eocene *p.p.* – late Eocene *p.p.*) is a red to white succession of marly limestone and marl (Figure 6m), while the Scaglia Cinerea Fm (late Eocene *p.p.* – Oligocene) is a grey marly unit. Outcrops of these Tertiary units are severely deformed with foliation and S-C structures (Figure 6n). The younger Bisciaro Fm (Aquitanian – Burdigalian *p.p.*) and Schlier Fm (Burdigalian *p.p.* – early Messinian *p.p.*) only form sparse outcrops with limited extent on the map.

The Umbria-Marche Apennines were involved in chain building in the middle/late Miocene (Boccaletti et al., 1990). Chain building took place through eastward migration of thrust fronts, soon after followed by westward extension (Carminati & Doglioni, 2012 and references therein). Extensional faulting in the region began in the Pliocene and is still active, as demonstrated by intense seismic activity (Boncio et al., 1998). The easternmost sector of the chain, facing the Adriatic sea, has not yet become part of the post-orogenic extensional system.

4. Field data and discussion

In this section an overview and a brief discussion of the field data are presented.

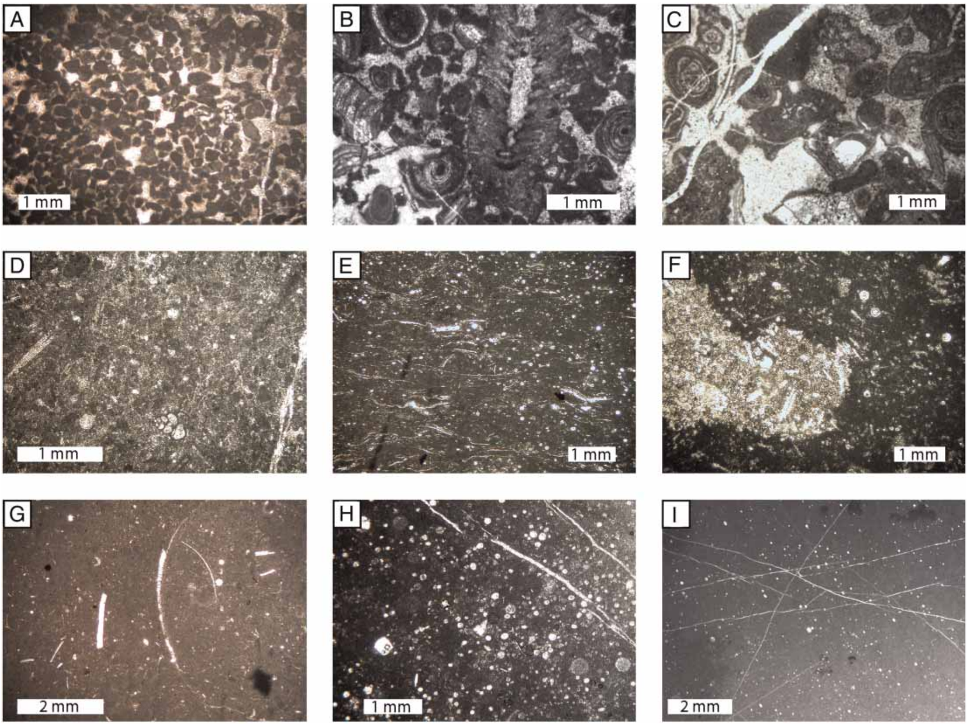

Figure 7. Photomicrographs of the main Mesozoic units described in the text: (A) Fine peloidal grainstone, with small ooids and benthic forams (Calcare Massiccio Fm, Pioraco); (B) Coarse oolithic grainstone, with *Palaeodasycladus mediterraneus* (Calcare Massiccio Fm, Mt. Primo); (C) Oolithic grainstone with with oncoids and bioclasts, partly affected by recrystallization (Calcare Massiccio Fm, Mt. Castel Santa Maria); (D) Fine peloidal packstone with sponge spicules, radiolarians and benthic forams (lower portion of the Corniola Fm, Pioraco); (E) Wackestone with abundant thin-shelled bivalves and radiolarians (Calcari e marne a *Posidonia* Fm, Mt. Castel Santa Maria); (F) Bioturbated cherty limestone with radiolarians, *Saccocoma* fragments and undetermined bioclasts (Calcari a *Saccocoma* e aptici Fm, Agolla); (G) Wackestone with radiolarians, fragments of *Saccocoma* sp., fragments of cephalopods and undetermined bioclasts (Calcari a *Saccocoma* e aptici Fm, Mt. Primo); (H) Wackestone with abundant radiolarians and calpionellids (Maiolica Fm, Agolla); (I) Radiolarian wackestone (Maiolica Fm, Mt. Primo); (J) Packstone with abundant undeterminable bioclasts (Maiolica Fm, Mt. Primo); (K) Coarse grained bioclastic turbidite passing upwards to a radiolarian wackestone (Maiolica Fm, Mt Primo); (L) Packstone with abundant mud fraction, microbial oncoids, *Tubiphytes*–like forms, benthic forams, sponge spicules and radiolarians are present along with undetermined bioclasts (Calcare Massiccio B Mbr, Mt. Cimara); (M) Peloidal packstone with benthic forams, large microbial oncoids and various bioclasts (Calcare Massiccio B Mbr, Mt Cimara); (N) Wackestone with bivalves, sponge spicules, ostracods, radiolarians and undetermined bioclasts (Calcari Nodulari dell'Infernaccio, Mt. Cimara); (O) Wackestone with sponge spicules, fragments of bivalves, ostracods, radiolarians and undetermined bioclasts (Calcari nodulari dell'Infernaccio, Sefro); (P) Packstone with abundant *Saccocoma* sp., small cephalopods, radiolarians and various bioclasts (Calcari nodulari ad ammoniti e aptici di Cava Bugarone, Mt. Primo); (Q) Wackestone with fragments of *Saccocoma* sp., small cephalopods, radiolarians and lithoclasts of Calcare Massiccio Fm (Calcari nodulari ad ammoniti e aptici di Cava Bugarone, Mt. Primo); (R) Wackestone with abundant radiolarians and calpionellids, fragments of cephalopods, fragments of aptychi, fragments of crinoids, molluscs and undetermined bioclasts (Calcari nodulari ad ammoniti e aptici di Cava Bugarone, Mt. Gualdo).

The main structural element in the study area is the Mt. Primo thrust, which is beautifully exposed eastward of the Mt Primo-Mt. Castel Santa Maria ridge, and continues beyond the surveyed area, both southwards and northwards (Calamita & Pierantoni, 1993). This element is

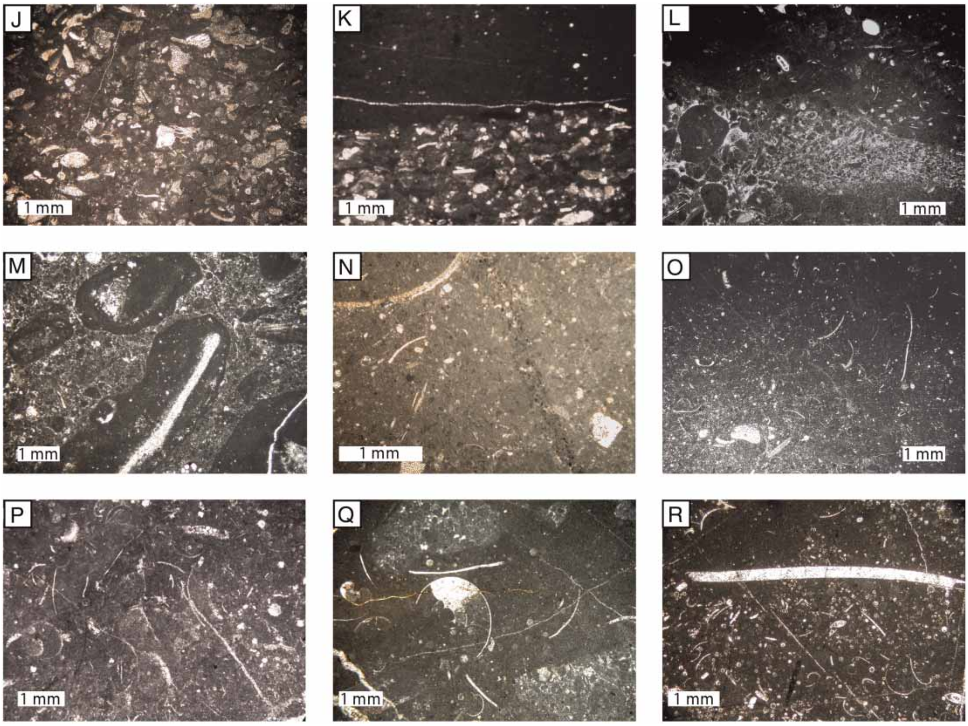

Figure 7. (Continued)

organized into three tectonic units (Calamita & Pierantoni, 1993): at the hangingwall the Mesozoic succession forms the Mt. Primo-Mt. Castel Santa Maria anticline; the intermediate unit is made up of several horses with Cretaceous-to-Miocene formations (Figure 8); the footwall of the thrust is the Camerino syncline (located eastward, outside the map area), where primarily Miocene terrigenous units crop out (Centamore, Chiocchini, Cipriani, Deiana, & Micarelli, 1978). Four main folds can be identified in the study area, from W to E:

- 1 – Massa–Passo Semegna syncline
- 2 – S. Cassiano-Mt. Cesito–Mt. Cimara anticline
- 3 – Agolla–Montelago syncline
- 4 – Mt. Primo-Mt. Castel Santa Maria anticline

Field analysis of structural elements revealed a N 60° direction for tectonic transport; the only structure oriented N-S is the Mt. Primo thrust (see also Calamita & Pierantoni, 1993); the ca. 60° angle between the thrust trend and the direction of tectonic transport results in a dextral transpression, a common feature in the region wherever the Calcare Massiccio occupies the core of anticlines. Thrust tectonics in the region were strongly influenced by the Jurassic stratigraphy (Cello, Deiana, Marchegiani, Mazzoli, & Tondi, 2000), as the Calcare Massiccio fault blocks represent a rheological discontinuity within the sedimentary succession. Thrusts commonly form ramp geometries within the rigid Calcare Massiccio (Calamita, Coppola, Deiana, Invernizzi, & Mastrovincenzo, 1987), with inherited Jurassic horsts being generally found at the hangingwall (Pierantoni et al., 2005). As a result of this, several positive structures in the region correspond to Jurassic structural highs.

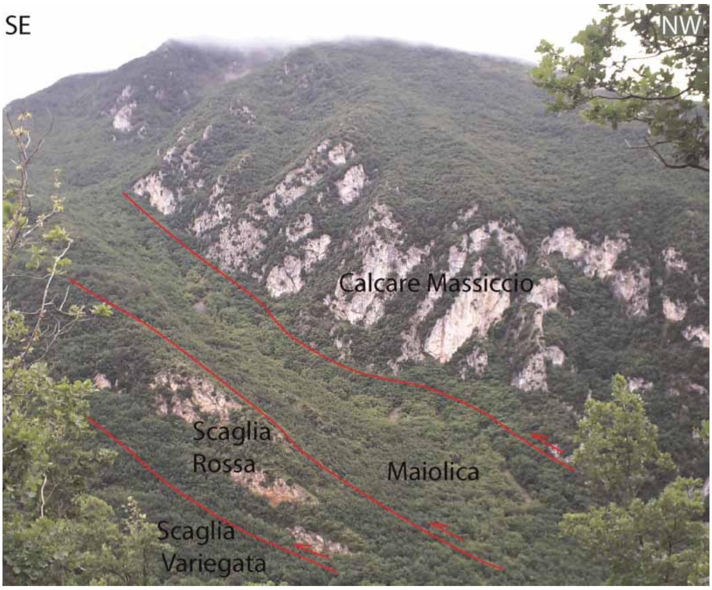

Figure 8. Panoramic view of the Mt. Primo thrust from Mt. Castel S. Maria eastern slope.

Jurassic rocks occupy most of the northern sector of the study area, forming a thick basinal succession north of the Potenza river, onlapping and eventually burying a Calcare Massiccio olistolith at Mt. Castel Santa Maria (Figure 9). The succession is cut by a main normal fault along the SW slope of Mt. Castel Santa Maria, and by a number of secondary faults in the Pioraco gorge. The lower part of the the Corniola Fm in this sector bears resedimented beds, massive to graded/laminated (Pioraco gorge), and is overlain by the pelagic succession from Rosso Ammonitico to the Maiolica. At Pioraco the lower portion of the basinal succession displays the vertical transition

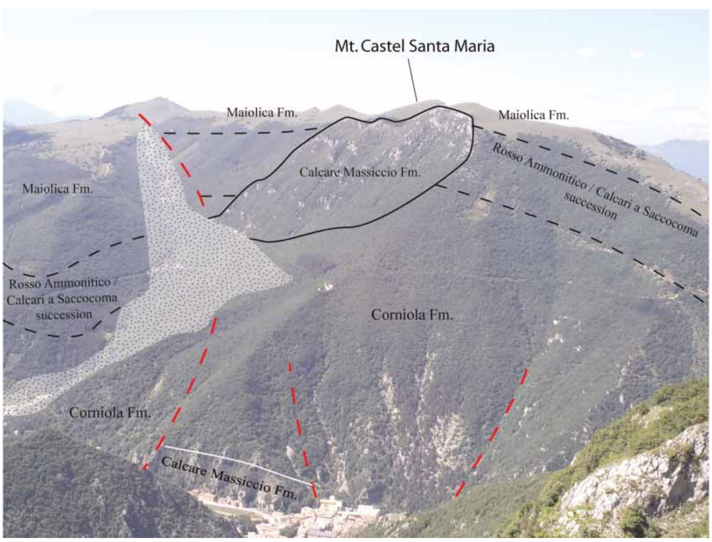

Figure 9. Geological interpretation of the southern slope of Mt. Castel Santa Maria.

from the Calcare Massiccio to Corniola Fm at the hangingwall of the Jurassic paleofault. The Calcare Massiccio is represented by low-angle clinoforms, suggesting that a short-lived phase of progradation took place when accommodation space was initially produced by synsedimentary extension, followed by sudden downfaulting of the proximal slope (Fabbi & Santantonio, 2012).

South of the Potenza river, the Mt. Primo and Mt. Gualdo ridges represent one (although partly dismembered by later tectonics) Calcare Massiccio paleostructure, surrounded by the Jurassic basinal succession. The northern slopes of Mt. Primo (Figure 10) expose a >650 m thick section of Calcare Massiccio Fm, which near the summit is unconformably overlain by scattered, patchy outcrops of 'Calcari nodulari dell'Infernaccio' and of 'Calcari nodulari ad ammoniti e aptici di Cava Bugarone'. This complex is overlain through an onlap contact by the Calcari a *Saccocoma* e Aptici and Maiolica Fms. The latter unit is characterized by a more than 60 m-thick interval of polygenic breccias, pebbly mudstones with large Maiolica intraclasts, and laminated calcarenites with abundant carbonate platform material (dasycladal algae, benthic forams). Along the stratigraphic contact, the Calcare Massiccio is thoroughly silicified, a feature that qualifies this surface as a preserved paleoescarpment tract (see above). The western slope of Mt. Primo is cut by two post-Jurassic normal faults, whose total displacement exceeds 300 m, causing the repetition of the above described situation at a lower elevation along the SE side of the Scarsito valley. At Mt. Gualdo, the Calcare Massiccio is onlapped by the Corniola to Maiolica basinal succession, with intense silicification along the paleoescarpment contact. Between Mt. Gualdo and Mt. Cimaiolo a very thin incomplete condensed succession is made by 'Calcari nodulari dell'Infernaccio', 'Calcari nodulari a filaments di Fosso del Presale' and 'Calcari nodulari ad ammoniti e aptici di Cava Bugarone', all topped by the Maiolica Fm. Silicification of both the Calcare Massiccio and the condensed units is a clue that the basal contact of the Maiolica is an unconformity, suggesting this particular area should represent the edge of the PCP (that is, the highest paleoescarpment tract), rather than its flat top. The 'Calcari nodulari ad ammoniti e aptici di Cava Bugarone' remarkably shows here faunas attributable to the late Berriasian (*Calpionellopsis* sp. and ammonoids of the family Berriasellidae), and has therefore a younger top than elsewhere in the region (the 'Calcari nodulari ad ammoniti e aptici di Cava Bugarone' typically has an early Kimmeridgian – late Tithonian age; Cecca et al., 1985; Cecca & Santantonio, 1986). The persistence of condensed facies up to the Early Cretaceous indicates that the Mt. Primo/Mt. Gualdo high stood proud of the sea bottom for a longer period of time than most other intrabasinal highs, before it became buried by the upper Maiolica. The Calcare Massiccio at Mt. Castel Santa Maria (Figure 11), is thoroughly silicified, and is not topped by any condensed successions whatsoever. Thin, laterally discontinuous patches of silicified

Figure 10. Panoramic view of the Mt. Primo and Mt. Gualdo ridges from Mt. Castel Santa Maria.

Figure 11. Lateral contact between the Calcare Massiccio and the Maiolica Fm at Mt. Castel Santa Maria.

'Calcari nodulari dell'Infernaccio' rest unconformably on the Calcare Massiccio, which is encased in the Corniola to Maiolica succession. This, and the proximity to the Mt. Primo-Mt. Gualdo structural high, suggest that this was not a Jurassic structural high (which would be separated by a very unlikely ~1 km-narrow and at least 800 m-deep basin from the Mt. Primo-Mt. Gualdo high), but should instead be considered a large olistolith.

North of Agolla, what appears as an isolated outcrop of Calcare Massiccio is fault-bounded to the west, but is onlapped by the Calcari a *Saccocoma* e Aptici and Maiolica Fms on its eastern side. Upon closer inspection, the onlap contact is in fact with a megabreccia (Figure 12), with silicified Calcare Massiccio boulders and discontinuous veneers of very condensed 'Calcari nodulari ad ammoniti e aptici di Cava Bugarone', whose rich ammonite fauna was described by Canavari (1891, 1896, 1897, 1898, 1900, 1903).

To summarize, since the relationships between the Calcare Massiccio and the basinal units at Mt. Gualdo-Mt. Primo and at Agolla are stratigraphic, but invariably unconformable, any direct evidence for a PCP-top environment, which would be documented by a laterally continuous condensed succession, is missing.

Between Sefro and Montelago, three Calcare Massiccio outcrops, severely deformed by both compressive and extensional faults, can be observed. The most intriguing outcrop is at Mt. Cimara, where a gradual Calcare Massiccio 'A'/Calcare Massiccio B transition occurs through a 40 m-thick interval, conformably covered by 'Calcari nodulari dell'Infernaccio', a few centimetres of 'Calcari nodulari e marne Verdi de I Ranchi', and 'Calcari nodulari ad ammoniti e aptici di Cava Bugarone'; its eastern boundary is silicified and onlapped by Calcari a *Saccocoma* e Aptici Fm and Maiolica Fm. This can be interpreted as a genuine PCP (top/edge) succession, E-bounded by a paleoescarmpent. South of Sefro, along the Scarsito valley, overlying a limited Calcare Massiccio 'A' outcrop, the succession is made by conformable Calcare Massiccio B, 'Calcari nodulari dell'Infernaccio' and 'Calcari nodulari e marne Verdi de I Ranchi', with a total thickness of not more than 20 m. This can be interpreted as the vestige of a PCP-top succession. Mt. Cesito is made of Calcare Massiccio Fm, locally silicified and onlapped by the Maiolica Fm. The Mt. Cesito Calcare Massiccio overthrusts the Cretaceous units of the Agolla-Montelago syncline. The latter three outcrops of Calcare Massiccio most likely represent different portions of the same Jurassic structural high, fragmented and displaced by Apenninic tectonics.

5. Jurassic paleogeography

Analyzing the collected data, following the guidelines described in Santantonio (1993, 1994) and Galluzzo and Santantonio (2002), a tentative reconstruction of the Jurassic PCP-Basin systems of the study area can be attempted. The original setting is deeply modified by Apennine tectonics

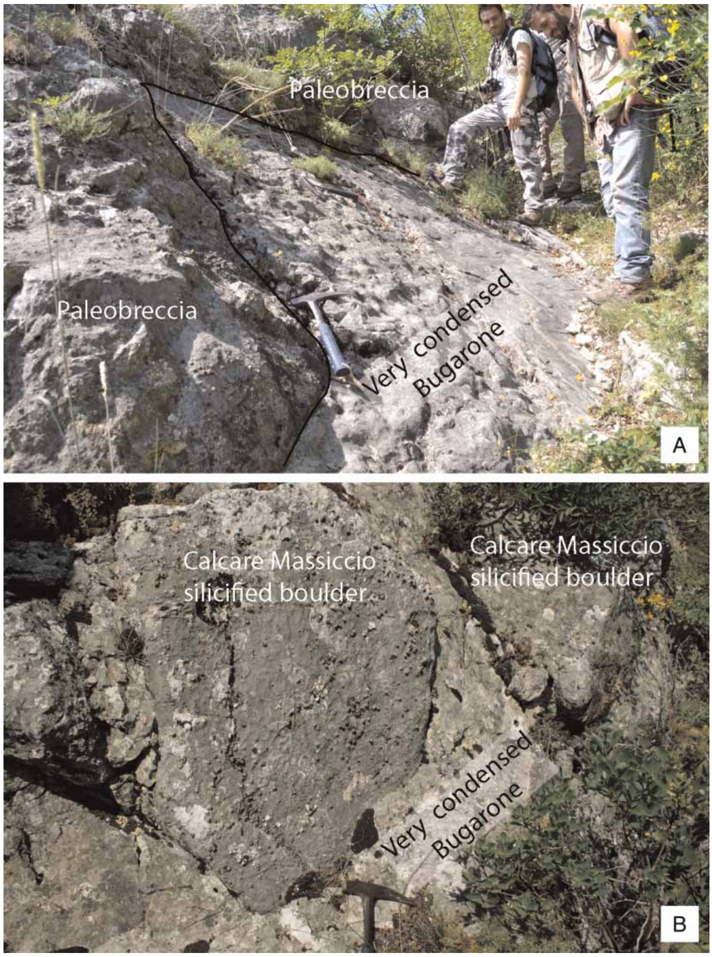

Figure 12. Field views of the Agolla megabreccia.

(Figure 13), and only two very limited portions of the PCP-top condensed succession can be observed; paleoescarpment outcrops, by contrast, are widespread.

Although dismembered by tectonics, the Mt. Primo-Mt. Gualdo area must represent, as a whole, one Jurassic structural high, delimited by mappable paleoescarpments. An S-dipping paleoescarment can be identified both at Mt. Primo and at Mt. Gualdo, marked by silicification at the Maiolica/Calcare Massiccio boundary. A N- and NE-dipping paleoescarpment can be mapped along the Potenza river valley, onlapped by the entire Jurassic basinal, megablock-bearing, succession. The top of this structural high should be roughly positioned at the vertical of the Potenza valley, and is therefore not visible due to erosion. The Mt. Primo-Mt. Gualdo high was entirely surrounded by deeper-water areas.

South of Mt. Gualdo-Mt. Primo, Jurassic outcrops are scattered. At Agolla the Calcare Massiccio is covered by a thoroughly silicified Calcare Massiccio paleobreccia, topped by epibreccia condensed deposits (sensu Galluzzo & Santantonio, 2002) and finally by basinal units. It is difficult to relate this outcrop with other Calcare Massiccio outcrops in the area, due to its limited extension and to the fact that it is surrounded only by the Maiolica Fm, which prevented assessment of the existence of any interposed Jurassic basin. The three southernmost Calcare Massiccio

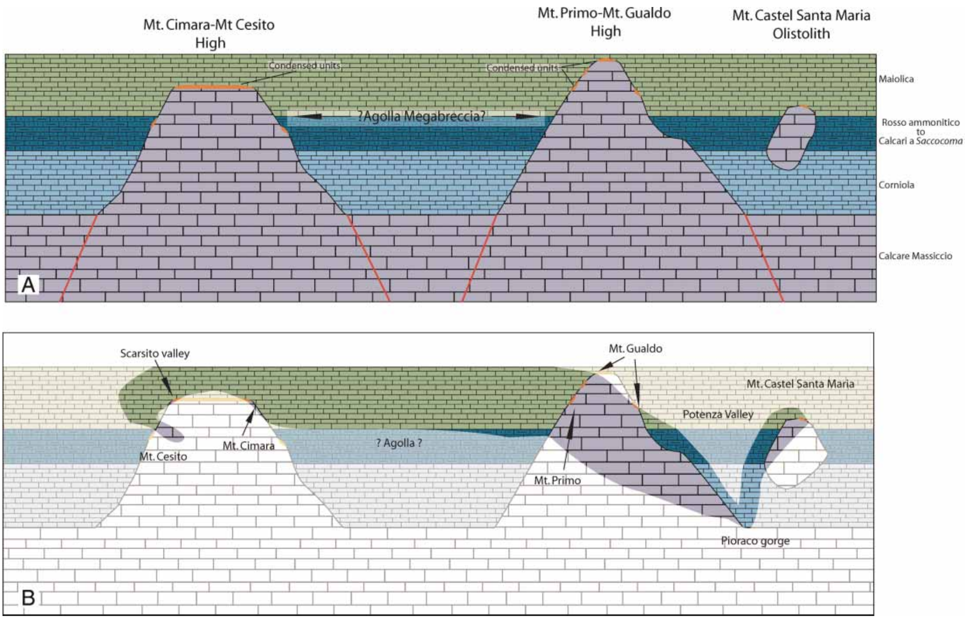

Figure 13. Schematic simplified cross-section reconstruction of the Jurassic paleogeography across Mt. Primo and neighbouring areas (A), and portions of the succession presently exposed in the study area (B).

outcrops most likely had to belong to the same structural high, that had to be different from the Mt. Primo-Mt. Gualdo high, which is clearly bordered to the south by a paleoescarpment. This structural high is now totally dismembered by tectonics, and any tentative reconstruction of its original geometries would be purely speculative.

6. Conclusions

A detailed 1:15,000 scale geological map of a sector of the northern Apennines is presented here, demonstrating the complex Jurassic paleogeographic setting resulting from the Hettangian-Sinemurian extensional phase, that produced a pattern of small isolated structural highs surrounded by deeper basins. In the study area two Jurassic structural highs have been identified, at Mt. Primo-Mt. Gualdo and at Mt. Cesito-Mt. Cimara. The first one is N-bounded by a Jurassic basinal succession, that bears a large Calcare Massiccio olistolith. The culmination of this high was eroded by the Potenza river, and only its marginal paleoescarpments are preserved. The presence of Early Cretaceous condensed deposits suggests that a marked submarine relief had to exist, which is consistent with the occurrence of a very large olistolith in the basin (Mt. Castel Santa Maria). Only very limited portions of the top of the southern high crop out, with this paleoelement thoroughly dismembered by tectonics.

The whole surveyed area was severely affected by Apenninic compression, and the presence of rigid Calcare Massiccio blocks, inherited from the Early Jurassic extensional phase, had an impact on the thrust trajectories.

Software

The map has been drawn using Adobe Illustrator CS2 from scanned hand-drawn maps. The topographic base has been simplified and partly redrawn from the Marche Region CTR at 1:10,000 scale (available online).

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